Chapter 14 Electromagnetic Induction

Faraday for the first time gives the concept of Electromagnetic induction.

It is well known that whenever an electric current flow through a conductor, a magnetic field is immediately brought into existence in the space surrounding the conductor. The converge of this is also true, i.e., when a magnetic field embracing a conductor moves relative to the conductor, it produces a flow of electrons. This phenomenon whereby an emf and hence current (i.e. flow of electrons) is induced in any conductor that is cut across or is cut by magnetic lines of force (magnetic flux), is known as ***electromagnetic induction.***

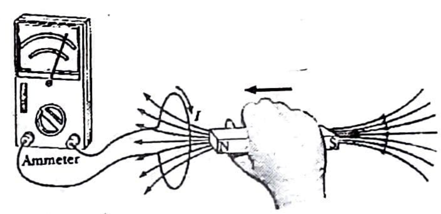
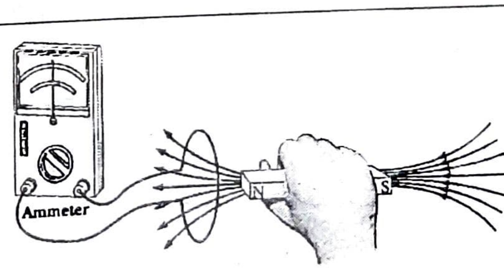
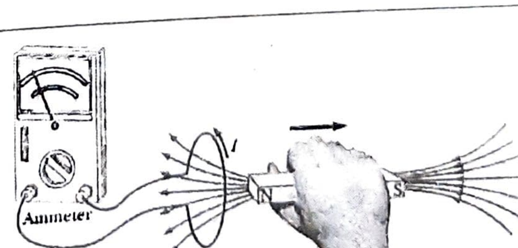
⇒ ***The basic requirement for induced current (electromagnetic induction) is changing of magnetic flux through a coil,***

⇒ ***if there is no change in flux there will be no induced emf or induced current.***

Important: *The existence of a magnetic flux through an area is not sufficient to create an induced emf. There must be a change in the magnetic flux in order for an emf to be induced.*

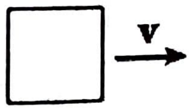
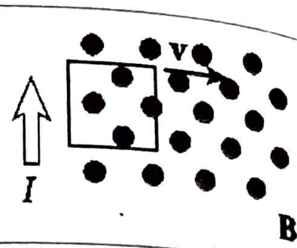
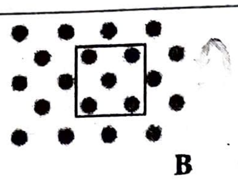
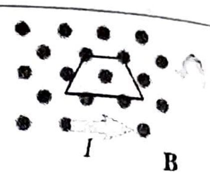
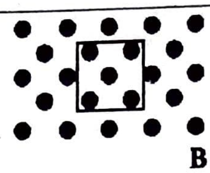
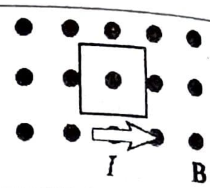
⇒ a current is set up even though no batteries are present in the circuit! We call such a current and ***induced current*** and say that it is produced by an ***induced emf.***

⇒ Following experiment (Faraday's Experiment) show production of induced emf in different cases;

Condition	Obesrvation
When a magnet is moved toward a loop of wire connected to a sensitive ammeter, the ammeter deflects as shown, indicating that a current is induced in the loop.	
When the magnet is held stationary, there is no induced current in the loop, even when the magnet is inside the loop.	
When the magnet is moved away from the loop, the ammeter deflects in the opposite direction, indicating that the induced current is opposite that shown.	
If the conductor is moves parallel to change in magnetic flux;	There will be no induced emf.

Ways of Inducing a Current in a Circuit

Description	Before	After

Circuit is moved into or out of magnetic field (either circuit or magnet moving).		
Circuit is rotated in the magnetic field (angle between area of circuit and magnetic field changes).		
Intensity and/or direction of magnetic field is varied.		

Flux linkages:

- ✓ Flux linkage is the product of number of turns of the coils with magnetic flux linking the coil.
- ✓ Mathematically;

$$Flux\ linkages = N\phi$$

Experimental observations

⇒ Experiments shows that magnitude of induced emf in a coil is directly proportional to the rate of change of flux linkages.

$$Induced\ Emf \propto Rate\ of\ change\ of\ flux\ linakges$$

$$Induced\ emf \propto \frac{N\phi_2 - N\phi_1}{t}$$

N is number of turns of the coils, and $\phi_2 - \phi_1$, shows that magnetic flux linking the coil changes from $\phi_1\ to\ \phi_2$ in t seconds.

Faraday's Laws of Electromagnetic induction

⇒ Faraday gives two laws, that explained electromagnetic induction.

⇒ These laws are success of series of experiments that faraday performed.

First Law

- ✓ According to this law; "when magnetic flux linking the coil changes and emf is induced in the coil, this emf lasts so long as the change in ***magnetic flux linking the coil continues***".
- ✓ ***Production of emf does not depends upon*** "How magnetic flux change is brought?".

Second law

- ✓ Second law is about magnitude of emf induced in coil.
- ✓ It states that "Magnitude of induced emf is directly proportional to flux linkages".

$$Induced\ emf \propto \frac{N\phi_2 - N\phi_1}{t}$$

$$Induced\ emf = k\frac{N\phi_2 - N\phi_1}{t}\ as\ K = 1\ so \Rightarrow Induced\ emf = \frac{N\phi_2 - N\phi_1}{t}$$

- ✓ ***We can also write this law in differential form;***

$$Induced\ emf = N\frac{d\phi}{dt}$$

- ✓ ***Induced emf in terms of frequency;***

$$\varepsilon = \phi B r^2 f$$

- ✓ ***This law implies that;***

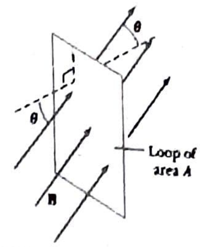
$$Induced\ emf \propto Number\ of\ turns\ of\ the\ coil$$

$$\text{Induced emf} \propto \text{Rate of change of magnetic flux}$$

✓ *We generally write this law in the form of;*

$$\text{Induced emf} = -N\frac{d\phi}{dt}$$

Where minus (−) sign of the right-hand side gives us direction of induced emf, which is explained by Lenz's Law.



A conducting loop that encloses an area A in the presence of a uniform magnetic field B. The angle between B and the normal to the loop is θ.

✓ ***Suppose that a loop enclosing an area A lies in a uniform magnetic field B, the magnetic flux through the loop is equal to BA cos θ; hence, the induced emf can be expressed as;***

$$\varepsilon = -\frac{d}{dt}(BA\cos\theta)$$

From this expression, we see that an emf can be induced in the circuit in several ways:

- The magnitude of B can change with time.
- The area enclosed by the loop can change with time.
- The angle # between B and the normal to the loop can change with time.
- Any combination of the above can occur.

✓ Relationship between induced charge and change in magnetic flux is given by;

$$|e| = \frac{d\phi}{dt}$$

$$\text{as } I = \frac{e}{R} \text{ or } \frac{dQ}{dt} = \frac{d\phi}{dt}\cdot\frac{1}{R} \quad \text{so Induced charge}, dQ = \frac{d\phi}{R}$$

So induced charge is equal to change in magnetic flux divided by resistance.

✓ Hence, we can say that;

$$\text{Induced charge due to change in magnetic flux} \propto \frac{1}{\text{Resistance of the coil}}$$

Direction of induced emf and current

Direction of induced emf and induced current is given;

1. Lenz's Law
2. Fleming's Right hand rule

Lenz's Law

⇒ Faraday's law indicates that the induced emf and the change in flux have opposite algebraic signs.

⇒ It states that; The induced current in a loop is in the direction that creates a magnetic field that opposes the change in magnetic flux through the area enclosed by the loop".

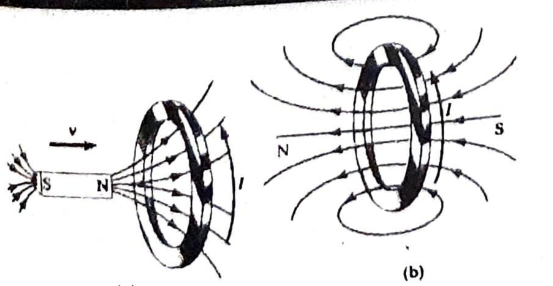
⇒ Lenz's law mathematical form;

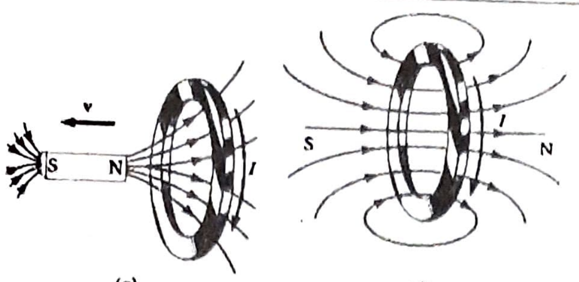
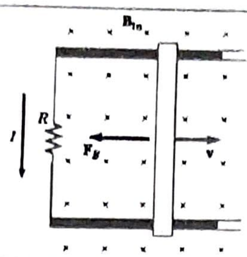
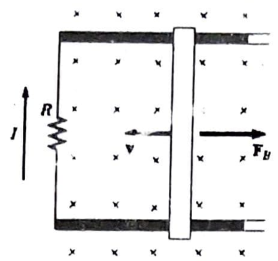
$$\varepsilon = -N\frac{d\phi}{dt}$$

The negative sign shows that magnitude of induced emf or current is opposite to the direction of changing magnetic flux.

⇒ Lenz's law follows law of conservation of energy.

⇒ Some Cases that explains Lenz's Law;

Case	Description
	(a) When the magnet is moved toward the stationary conducting loop, a current is induced in the direction shown. The magnetic field lines shown are those due to the bar magnet. (b) This induced current produces its own magnetic field directed to the left that counteracts the increasing external flux. The magnetic field lines shown are those due to the induced current in the ring.

 (c) (d)	(c) When the magnet is moved away from the stationary conducting loop, a current is induced in the direction shown. The magnetic field lines shown are those due to the bar magnet. (d) This induced current produces a magnetic field directed to the right and so counteracts the decreasing external flux. The magnetic field lines shown are those due to the induced current in the ring.
	(a) As the conducting bar slides on the two fixed conducting rails, the magnetic flux due to the external magnetic field into the page through the area enclosed by the loop increases in time. By Lenz's law, the induced current must be counterclockwise so as to produce a counteracting magnetic field directed out of the page.
	(b) When the bar moves to the left, the induced current must be clockwise. Why?

Fleming Right hand rule

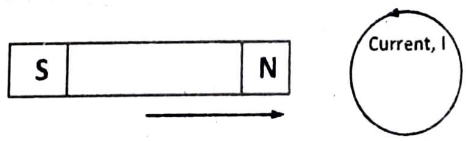
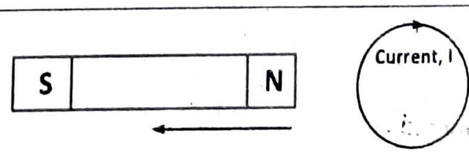
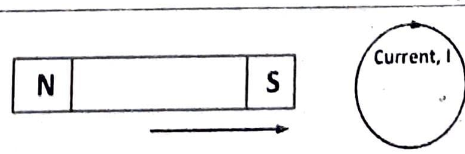
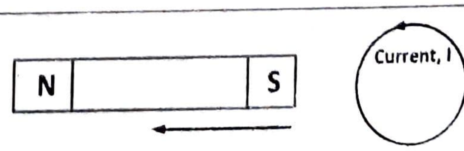
⇒ This rule is suitable to find the direction of induced current/emf when the conductor moves at right angle to the stationary magnetic fields.

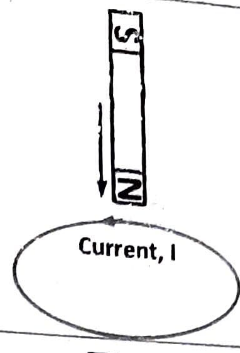
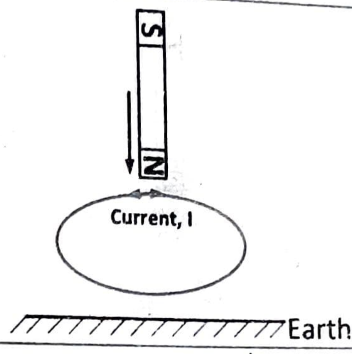
⇒ ***This rule states that;***

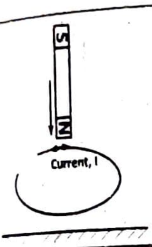
Stretch out forefinger, middle finger and thumb of your right hand at right angle then;

Forefinger	Thumb	Middle finger
⇒ direction of $\vec{B}$	⇒ direction of motion of conductor	⇒ induced current

Some important cases of induced current for entrance exams;

Cause (Magnet motion)	Direction of cuurent	Diagram	Acceleration
Forward	Anticlockwise		–
Reverse	Clockwise		–
Forward	Clockwise		–
Reverse	Anticlockwise		–

Downward	Anticlockwise		$a < g$
Downward	Anticlockwise ↓ Clockwise		$a < g$



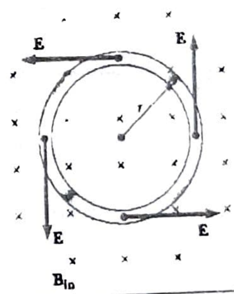
if the coil is cut in this case $a = g$ and no current will flow through it because circuit is incomplete.

Induced emf and Electric Fields

⇒ In our study of electricity, we related a current to an electric field that applies electric forces on charged particles.

⇒ In the same way, we can relate an induced current in a conducting loop to an electric field by claiming that an electric field is created in the conductor as a result of the changing magnetic flux.

⇒ We also noted in our study of electricity that the existence of an electric field is independent of the presence of any test charges. This suggests that even in the absence of a conducting loop, a changing magnetic field would still generate an electric field in empty space.



A conducting loop of radius r in a uniform magnetic field perpendicular to the plane of the loop. If **B** changes in time, an electric field is induced in a direction tangent to the circumference of the loop

⇒ This induced electric field is nonconservative, unlike the electrostatic field produced by stationary charges.

⇒ The induction of a current in the loop implies the presence of an induced electric field E, which must be tangent to the loop because this is the direction in which the charges in the wire move in response to the electric force.

⇒ The work done by the electric field in moving a test charge q once around the loop is equal to $q\varepsilon$. Because the electric force acting on the charge is qE, the work done by the electric field in moving the charge once around the loop is $qE(2\pi r)$, where $2\pi r$ is the circumference of the loop. These two expressions for the work done must be equal; therefore,

$$qE = qE(2\pi r)$$

$$E = \frac{\varepsilon}{2\pi r}$$

AS $\phi = BA = B\pi r^2$

$$E = -\frac{1}{2\pi r}\frac{d\phi}{dt} = -\frac{r}{2}\frac{dB}{dt}$$

If the time variation of the magnetic field is specified, we can easily calculate the induced electric field from this Equation.

Induced emf

According to faraday, whenever a conductor is placed in a varying magnetic field. EMF is induced in the conductor called induced emf.

Types of Induced emf (On the basis of variation in magnetic field)

1. Dynamically induced emf
2. Statically induced emf

Dynamically induced emf	⇒ *when conductor is moved in a stationary magnetic field in such a way that* flux linkages *changes in magnitude.* ⇒Here conductor or coil is moving but magnetic field is at rest. Example: DC generator, Motional emf
Statically induced emf	⇒ *when conductor is stationary and the magnetic field is moving or changes.* ⇒Here conductor or coil is at rest but magnetic field is moving or changing.

Various methods of producing Induced Emf

⇒ As we know that magnetic flux linking the coil changes then emf will be induced in that coil.

⇒ The magnetic flux through coil for one turn is given by;

$$\phi = BA\cos\theta \text{ where } B \rightarrow \text{Magnetic flux density}, A \rightarrow \text{area of coil},$$
$$\theta \rightarrow \text{angle between } B \text{ and normal to the area}$$

⇒ Magnitude of Induced emf calculated by faraday is given by;

$$\varepsilon = \frac{d\phi}{dt} = \frac{d}{dt}(BA\cos\theta)$$

⇒ The above equations show that, emf can be induced in the circuit by the following ways;

i. As $\varepsilon \propto \vec{B}$. As magnetic flux linking the coil increases the induced emf will be also increases.so;

ii. emf can be induced by changing area of the coil.

iii. It can be also change by changing orientation of the coil w.r.t magnetic field. (By changing θ)

Magnetic motion	*Result*
Magnet is moved toward coil	ε *induced will be increases*
Magnet is moved away from the coil	ε *induced will be decreases*

Motional emf

⇒ The emf induced in a conductor due to its motion in magnetic field is called motional emf.

⇒ It is so called Motional, because motion of conductor is involved.

⇒ If the conductor forms a closed loop, then induced current will flow through it.

⇒ Magnitude of induced emf (Motional emf) can be found by three ways;

- ✓ Using Faraday's law
- ✓ Using the concept of magnetic Lorentz force
- ✓ Using principle of Law of conservation energy

⇒ Let say if conductor of length 'l' is moving with velocity $\vec{v}$ at right angle to the uniform magnetic field. Suppose the conductor moves a small distance dx *in time* dt,

$$\text{The area covered by conductor is given by} = l \times dx$$
$$\text{Magnetic flux covered} = d\phi = B \times (l \times dx) \Rightarrow Bldx$$

According to faraday's law, Emf is given by;

$$\varepsilon = N\frac{d\phi}{dt} = \frac{Bldx}{dt} = Blv \qquad \text{as } v = \frac{\text{small displacement}}{\text{time}} = \frac{dx}{dt} \Rightarrow d \rightarrow \text{small change}$$

Hence:

$$\varepsilon = Blv$$

Induced current in terms of motional emf;

$$I = \frac{\varepsilon}{R} = \frac{Blv}{R}$$

⇒ If the conductor moves at an angle θ to the magnetic field the velocity at which the conductor moves across the field is given as $v\sin\theta$

$$\varepsilon = Blv \sin\theta$$

⇒ *If angular velocity is given, then;*

$$\varepsilon = Blv = Blr\omega \qquad (As\ v = r\omega)$$

⇒ If the conductor is moving with uniform velocity net force on it is zero.

⇒ If conductor is moved parallel to magnetic field there will no flux linkage, hence induced emf will be zero.

⇒ Note that induced emf will be maximum if B, l *and* v are mutually perpendicular.

⇒ If the direction of $\vec{B}$ *and* $\vec{v}$ is reversed then the direction of induced emf will be also reversed.

Trick:

✓ The mechanical power (Heat energy produced per second) needed to move the loop of magnetic field 'B' with constant velocity $\vec{v}$, is given by;

$$As\ \varepsilon = Blv;\ I = \frac{\varepsilon}{R} = \frac{Blv}{R}$$

$$As\ F = IlB = \left(\frac{Blv}{R}\right)lB = \frac{B^2l^2v}{R} \quad \therefore P = Fv = \left(\frac{B^2l^2v}{R}\right)v = \frac{B^2l^2v^2}{R}$$

✓ Lorentz magnetic force on free electron acts toward the south end of the wire.

Inductance

⇒ Inductance is; "The property of electrical circuits which opposes any change in the current in the circuit".

⇒ Inductance is inherent property of electrical circuits. It will always be found in an electrical circuit whether we need it or not.

⇒ If a wire is carrying current and have no iron, then the value of inductance will be low for that wire.

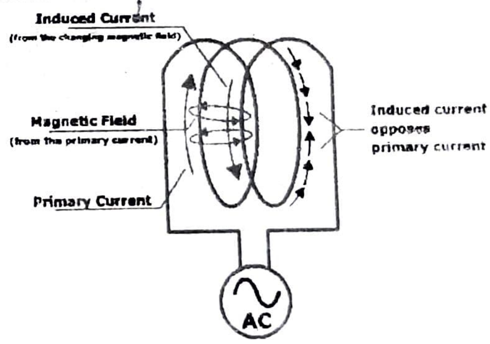
⇒ Inductance is analogous to inertia in mechanics, because inductance of an electrical circuit opposes any change of current in the circuit.

Two types of inductance

1. Self-inductance
2. Mutual inductance

Self-Induction (Qualitative) and Self-Inductance (Quantitative):

⇒ We know that when current through the coil changes ⇒ there occur changes in magnetic flux ⇒ when magnetic flux linking the coil changes ⇒ it produces induced emf called self-induced emf.



⇒ The emf produced here is called opposing emf, because it opposes the change of current in the circuit.

⇒ If current in the coil increases, the induced emf produced in such direction so as to oppose the increase in current (it will be in a direction to decrease the current). ***In this case it will be in direction opposite to voltage.***

⇒ If current in the coil decreases, the induced emf produced in such direction so as to oppose the decrease in current (it will be in a direction to increase the current). ***In this case it will be in direction of voltage.***

⇒ *Self-Inductance:*

✓ It is the property of a coil by virtue of which it opposes any change in the amount of current flowing through it.

✓ It is represented by 'L'.

✓ 1st expression of self-inductance: If we have a coil having "N" number of turns and magnetic flux through each turn is ϕ then experimentally it is found that:

$$\text{Flux linkage} \propto \text{Current}$$

$$N\phi \propto I$$

$$N\phi = LI \Rightarrow L = \frac{N\phi}{I} \quad (\textit{Where L is coefficient of self inductance})$$

✓ 2nd expression of self-inductance: if changing current through a coil having N number of turns produces self-induced emf ε_s then;

$$\varepsilon_s = L\frac{dI}{dt} \Rightarrow L = -\frac{\varepsilon_s}{dI/dt}$$

✓ If $\frac{dI}{dt} = 1$ "Rate of change of current is equal to unity" then self-inductance of a coil is equal to self-induced emf ($\varepsilon_s = L$).

✓ Hence, we can say that, "Value of self-inductance depends upon":

i. Dimension of the coil (Area, length, volume)

ii. Number of turns of the coil.

iii. Nature of core material of the coil.

✓ ***it is scalar quantity.***

✓ ***Units:***

Si unit is "Henry".

$$if\ \frac{I}{t}\left(\frac{Current}{time}\right) = 1\frac{A}{s}\left(\frac{Ampere}{second}\right)\ and\ \varepsilon_s = 1V\ then\ L = 1Henry$$

Smaller unit of inductance are (millihenry) and (microhenry).

✓ ***Dimension:*** $[L] = [ML^2T^{-2}A^{-2}]$

Some extra points

➢ Note that the coil whose inductance is very large and resistance is negligible s called as inductor or choke coil.

➢ **Inductance of a long solenoid:**

$$L = \frac{\mu_o N^2 A}{l} = \frac{\mu_o \mu_r N^2 A}{l}$$

➢ **Energy stored in inductor:**

$$U = \frac{1}{2}LI_o^2\ (I_o \rightarrow final\ value\ of\ current)$$

➢ The energy stored in inductor is supplied by emf source.

➢ Energy in an inductor can be considered as to be energy stored in magnetic field.

➢ When current in the coil is zero the emf induced in L is zero, however the energy stored in inductor is given by $\frac{1}{2}LI_o$.

Mutual-Induction (Qualitative) and Mutual-Inductance (Quantitative):

⇒ It is the property of two neighboring coil (One is primary second is called secondary) to induce voltage in one coil by changing current in the other is called Mutual induction.

⇒ ***Mutually induced emf:*** "the emf induced in a coil due to changing current in the neighboring coil and is called mutually induced emf".

⇒ The emf induced through mutual induction exists in coil as long as the current in another coil is keep changing.

⇒ If the current through the coil become steady (do not changes), due to this the mutual flux also becomes constant and so the mutually induced emf becomes zero.

⇒ *Mutual Inductance:*

✓ ***The equation for mutual inductance is;*** *Mutual inductance is equal to flux linkage in 1 coil when a unit current flows in the other coil.*

$$N_2\phi_2 = MI_1 \Rightarrow M = \frac{N_2\phi_2}{I_1}$$

Where N_2 is number of turns of the 2nd coil, ϕ_2 is flux through 2nd coil, and I_1 current flowing through coil A. $(Note\ that\ M\ is\ constant, and\ is\ known\ as\ co-efficient\ of\ mutual\ inductance)$.

✓ $If\ I_1 = 1\ then\ M = N_2\phi_2$ hence if current flowing through 1st coil is 1 Ampere, then co-efficient of mutual inductance is equal to product of number of turns in 2nd coil and magnetic flux through 2nd coil.

✓ ***The equation for mutual inductance can also be written as;***

$$\varepsilon_M = -M\frac{dI_1}{dt} \Rightarrow M = -\frac{\varepsilon_M}{dI_1/dt}$$

✓ $if\ \frac{dI_1}{dt} = 1\ then\ Mutual\ inductance\ is\ equal\ to\ \varepsilon_M\ \ M = \varepsilon_M$

✓ ***Mutual inductance depends upon;***

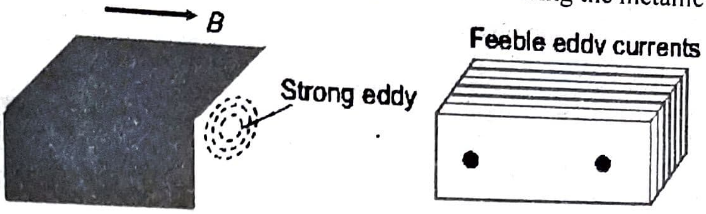
i. Number of turns (N_1, N_2) of both coils
ii. Area of cross-section of coils.
iii. Coefficient of self-inductances (L_1, L_2) of both the coils.
iv. Magnetic permeability of medium between the coils (μ_r) or nature of material on which two coils are wound.
v. Distance between two coils (As d increases so M decreases).
vi. Orientation between primary and secondary coil (for 90° orientation no flux relation M = 0)

✓ ***Units and dimensional formula of M:*** Similar to self-inductance (L).

Eddy Current

⇒ Eddy current is the current induced in metallic masses when the magnetic flux linking the metallic masses changes.

⇒ Because the resistance of the metallic masses is usually low, eddy currents often have large magnitudes and heat up the conductor.



⇒ Experimental concept given by Focault hence also named as "Focault current".

⇒ These are circulating currents like eddies in water that's why it is called eddy current.

⇒ The production of eddy currents in a metallic block leads to the loss of electric energy in the form of heat.

⇒ Eddy current can produce considerable heating and magnetic effect.

⇒ ***Reduction of eddy currents:***

✓ In most of the cases there are some problem associated with eddy currents, like some time they produce heat in circuit which causes serious problems.

✓ As the magnitude of eddy current is given as;

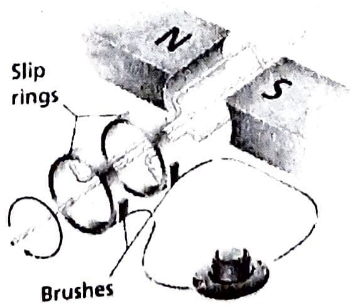
Single piece *Many piece*

$$I = \frac{\varepsilon(Induced\ emf)}{R(Resistance\ of\ eddy\ current\ path)} = -\frac{d\phi/t}{R}$$

✓ So, the magnitude of eddy current can be reduced by reducing induced emf and increasing Resistance.

✓ For this reason, the cores are not taken as a single piece of iron but are split into thin sheet called lamination, in planes parallel to the magnetic field.
This arrangement reduces area of each section and hence emf is reduced.
This arrangement also increases the resistance associated with eddy current path.

Alternating current generator or Alternator



⇒ AC generator converts mechanical energy into alternating current energy (Electrical).

⇒ **Principle:** it works on the principle of electromagnetic induction.

⇒ **Construction (Main component):**

i. ***Armature:*** An armature is rectangular coil having four sides. of insulated copper wire wound on a soft iron core. (Coil + Core = Armature).

ii. ***Strong field Magnet:*** A strong permanent magnet or an electromagnet whose poles (N and S) are cylindrical in shape in a field magnet. The armature coil rotates between the pole pieces of the field magnet. The uniform magnetic field provided by the field magnet is perpendicular to the axis of rotation of the coil.

iii. ***Current collector (Brushes and Slip rings):*** the two ends of armature are connected to copper rings called slip rings. This arrangement lead current that is induced to external circuit.

⇒ As the coil rotates anticlockwise at any time 't'.
The flux linking the coil is given by; $\phi = NABcos\theta \Rightarrow NAB\omega t$ as θ is time dependent and is changes with passage of time. So emf induced in the coil is also changing with the passage of time, so the current produced is alternating current.

⇒ Note that direction of induced emf changes periodically.

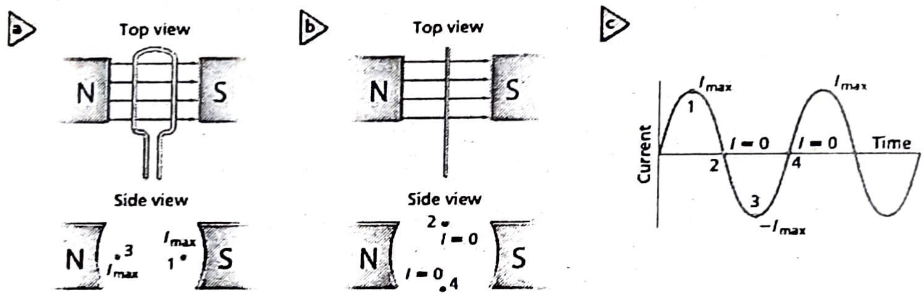
⇒ Magnitude of induced emf is given by;

$$\varepsilon = \varepsilon_o sin\omega t \Rightarrow \varepsilon_o = NAB\omega (Maximum\ value)$$

⇒ Instantaneous circuit current:

$$I = \frac{\varepsilon}{R} = \frac{\varepsilon_o sin\omega t}{R} = I_o sin\omega t$$

⇒ Induced emf and induced current for 1 cycle of AC generator, value of emf with passage of time is given;



The cross-sectional view of a rotating wire loop shows the position of the loop when maximum current is generated (a). When the loop is vertical, the current is zero (b). The current varies with time as the loop rotates (c). The variation of EMF with time can be shown with a similar graph.

Angle θ	*Angle in radian*	*Value of time*	*Induced emf ε*	*Induced current*	*Comments*
0°	0	0	$E = 0$	$I = 0$	Zero
90°	$\frac{\pi}{2}$	$\frac{T}{4}$	$E = +E_o$	$I = +I_o$	Maximum value
180°	π	$\frac{T}{2}$	$E = 0$	$I = 0$	Zero value
270°	$\frac{3}{2}\pi$	$\frac{3T}{4}$	$E = -E_o$	$I = -I_o$	Maximum value
360°	2π	T	$E = 0$	$I = 0$	Zero value

⇒ Hence it is clear that when the plane of the coil is perpendicular to the direction of magnetic field then induced emf will be maximum.

⇒ Each emf and current have a phase difference of about 90°.

⇒ Note that the maximum value of $sin\omega t = 1$.

⇒ We usually measure the θ from the position of the coil when its plane is perpendicular to the direction of magnetic field.

Some important equations;

Current induced by generators	$I = \frac{\varepsilon}{R} \Rightarrow I = I_o sin\omega t \Rightarrow I = I_o sin2\pi ft$
Emf produced by generators	$\varepsilon = N\omega ABsin\theta \Rightarrow \varepsilon = N\omega ABsin\omega t \Rightarrow \varepsilon = N\omega ABsin2\pi ft$
Maximum value of Emf	$\varepsilon_o = N\omega AB \Rightarrow \varepsilon_o = NAB2\pi f$

Alternating current Motor (AC motor)

⇒ It converts electrical energy into Mechanical energy.

⇒ Based on torque on a current carrying conductor, $\tau = NIAB$ (Motor effect)

⇒ *Ac motor has two basic parts;*

1) Stator (Stationary part)
   It is the part that is directly connected with the source.
2) Rotor (Moving part) ⇒ it consists of a coil wounds on a laminated iron armature mounted on an axle.
   No source is connected to it, it is because Rotor rotates that's why magnetic field induce current in it.

⇒ Current induced due to motion of rotor, this current is a result of consecutive motion of rotor around a stator on which individual electromagnets are arranged in such a way that they form a hollow cylinder with one pole o each magnet facing towards the center of the group.

⇒ Rotor also consists of some other magnets arranged around cylinder with the poles facing towards the stator pole.

⇒ Each time when the polarity of stator is changes (because the current is AC) then it forces the rotor to rotates at 60° around the stator.

⇒ Back emf in AC motor

- ✓ As we know that when rotor rotates it induces current and hence emf which is called induced emf.
- ✓ We also know from Lenz's law when there is production of induced emf, at same time there will be another emf in this case we called back emf, whose direction will be opposite to the direction of induced emf.
- ✓ $Back\ emf < emf\ of\ Source$
- ✓ $Back\ emf = Applied\ emf\ (if\ resistance\ is\ negligible)$
- ✓ As the potential of source is given as;

$$V_{source} = IR + \varepsilon \Rightarrow I = \frac{V - \varepsilon}{R} \Rightarrow I = \frac{V - N\omega ABsin\theta}{R}$$

- ✓ As we know that magnitude of induced emf in motor is given by;

$$\varepsilon = N\omega ABsin\theta$$

$$so, \varepsilon \propto \omega(angular\ speed\ of\ rotor)$$

- ✓ ***Mechanical power and Efficiency of AC motor:***

$$Efficiency, \eta = \frac{P_{mechanical}}{P_{supplied}} = \frac{P_{out}}{P_{in}} = \frac{\varepsilon_{Back}}{E_s} = \frac{Back\ emf}{Source\ emf}$$

Transformer

⇒ A device used to step up or step-down voltage/current is called transformer.

⇒ Principle: it works on the principle of mutual induction.

⇒ It obeys law of conservation of power.

⇒ Transformer usually consists of two kinds of windings,

1) Primary winding/coil: Connected to AC source
2) Secondary winding/coil: usually connected to load.

1) There is no electrical connection between primary and secondary coil.
2) It is only magnetic flux that helps us to transferred ac power from primary coil to the secondary coil.
3) The number of turns of primary and secondary coils enable us, whether we have raised voltage/step-up voltage or step-down voltage.
4) Transformer does not change the frequency of input ac.
5) Effective resistance between primary and secondary winding is infinite.
6) The flux per turn of each coil must be same i.e. $\phi_s = \phi_p$.
7) ***The principle equation for transformer is;***

$$\frac{\varepsilon_{secondary}}{\varepsilon_{primary}} = \frac{N_{secondary}}{N_{primary}} = \frac{V_s}{V_p} = \frac{I_p}{I_s} = k(Transformation\ ratio\ or\ turn\ ratio)$$

8) This equation is based for ideal transformer for which;

$$P_{output} = P_{input} \Rightarrow V_s I_s = V_p I_p \Rightarrow and\ so, v_p \approx \varepsilon_p\ and\ v_s \approx \varepsilon_s$$

9) ***Depending upon the capability of transformer to raise up or down voltage there are two types of transformer;***

Stepup transformer	Stepdown transformer
It increases voltage.	It decreases voltage.
It decreases current.	It increases current.
Applied voltage $\rightarrow V_s > V_p$	Applied voltage $\rightarrow V_s < V_p$
No of turns $\rightarrow N_s > N_p$	No of turns $\rightarrow N_s < N_p$
Induced emf $\rightarrow \varepsilon_s > \varepsilon_p$	Induced emf $\rightarrow \varepsilon_s < \varepsilon_p$
Induced current $\rightarrow I_s < I_p$	Induced current $\rightarrow I_s > I_p$
Resistance $\rightarrow R_s > R_p$	Resistance $\rightarrow R_s < R_p$

10) ***Efficiency of transformer:*** it is the ratio of output power to input power.

For ideal transformer: $\eta = 100\%$

$$\eta\% = \frac{P_{out}}{P_{in}} \times 100 = \frac{V_s I_s}{V_p I_p} \times 100 \Rightarrow it\ is\ efficiency\ of\ an\ ideal\ transformer$$

For practical transformer: $\eta = 70\% - 80\%$

$$P_{in} = P_{out} + P_{loses} \Rightarrow \eta = \frac{P_{out}}{P_{in}} \times 100 \Rightarrow \eta = \frac{P_{out}}{P_{out} + P_{losses}} \times 100 \Rightarrow \frac{(P_{in} - P_{losses})}{P_{in}} \times 100$$

11) ***Losses in transformer;***

1) When current flows through the transformer windings some power is wasted in the form of heat given as $H = I^2Rt$
2) Some electrical power is wasted in the form of heat due to eddy currents.
3) The alternating current flowing through the coils magnetizes and demagnetizes the iron core again and again. Therefore, during each cycle of magnetization, some energy is lost due to hysteresis.
4) Magnetic flux from primary coil not reach at all but some of it is leaked.

FORMULAS SHEET

1.	Motional emf	$E = -vBL\sin\theta$		
2.	Motional emf (maximum)	$E = -vBL$		
3.	Faraday's law (induced emf)	$\phi = -N\frac{\Delta\phi}{\Delta t}$		
4.	Magnetic flux through a current carrying coil	$N\phi = LI$		
5.	Mutual inductance	$\varepsilon_s = -M\frac{\Delta I_p}{\Delta t}$	$M = \frac{\varepsilon}{\Delta I_p/\Delta t}$	
6.	Self-inductance	$\varepsilon_s = -L\frac{\Delta I}{\Delta t}$	$L = \frac{\varepsilon}{\Delta I/\Delta t}$	
7.	Mutual induction	$N_s\phi_s = MI_p$	$M = \frac{N_s\phi_s}{I_p}$	$\varepsilon_s = -M\frac{\Delta I_p}{\Delta t}$
8.	Self-inductance of a coil	$L = \mu_o n^2 Al$		
9.	Energy stored in magnetic field	$U_m = \frac{1}{2}\frac{B^2}{\mu_o}(Al)$		
10.	Energy density of a magnetic field	$U_m = \frac{1}{2}\frac{B^2}{\mu_o}$		
11.	Emf produced by generator	$\varepsilon = N\omega AB\sin\theta$	$\varepsilon = N\omega AB\sin\omega t$	$\varepsilon = N\omega AB\sin 2\pi ft$
12.	Maximum emf produced by generator	$\varepsilon_o = N\omega AB$	$\varepsilon = \varepsilon_o\sin\omega t$	$\varepsilon = \varepsilon_o\sin 2\pi ft$
13.	Current produced by generator	$I = \frac{\varepsilon}{R}$	$I = I_o\sin\omega t$	$I = I_o\sin 2\pi ft$
14.	Back emf effect in motors	$I = \frac{V-\varepsilon}{R}$	$V = \varepsilon + IR$	
15.	Transformation ratio in transformer	$\frac{N_S}{N_P} = \frac{V_S}{V_P}$		
16.	Power transmission in transformer	$V_P I_P = V_S I_S$	$\frac{V_s}{V_p} = \frac{I_p}{I_s}$	
17.	Efficiency of transformer	$\eta = \frac{O.power}{I.power} x100$		

UNITS

1.	Mutual inductance	VsA^{-1}, WbA^{-1}	henry
2.	Self-inductance	VsA^{-1}, WbA^{-1}	henry

Some important points and tricks

1) The induced e.m.f is generated in an open circuit, but induced current is not produced in the open circuit.
2) Induced charge depends upon the change of magnetic flux not on the rate of change of ϕ.
3) In electromagnetic induction, e.mf is induced in a coil and mechanical energy is converted into electrical energy.
4) Eddy currents do not cause sparking.
5) Eddy currents are produced when the angle between metal surface and magnetic field, is 90 °.
6) Outward field always gives anticlockwise current and inward field gives clockwise current.
7) Transformer has highest possible efficiency out of all the electrical machines.
8) Equivalence between current carrying circular coil and magnetic dipole:
   i. Magnetic field produced by current carrying circular coil is similar to magnetic field of a short bar magnet.
   ii. When the current flow in the coil is anticlockwise, field at the centre is directed outwards, at right angle to face of coil. In this case, face of coil acts like north polarity
   iii. When the current flow in the coil is clockwise, field at the centre is directed inwards, at right angles to the face of coil. In this case. face of coil acts like south polarity'.
9) Potential energy' of a charged particle in a magnetic field always remain constant.
10) If a plane is parallel to the magnetic field, then no flux line will pass through it and the magnetic flux linked with that plane will be zero.
11) As electric current generates magnetic field, as per law of conservation of energy, magnetic flux should also generate electric current.
12) If applied field is increasing, induced field will be in opposite direction to that of applied field.
13) If applied field is decreasing, induced field will be in the same direction as of applied field.
14) Induced e.m.f can be due to change in field as well as change in area.
15) Self-inductance is a measure of electrical inertia as it opposes the variation of current.
16) If a.c. is produced by a generator having a large number of poles then its frequency

$$f = \frac{\text{Number of poles} \times \text{rotation per second}}{2} = \frac{p \times \omega}{2}$$

Where P is the number of poles; ω is the rotational frequency of the coil.